

Combined application of Life Cycle Assessment and linear programming to evaluate food waste-to-food strategies: seeking for answers in the nexus approach

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ABSTRACT

The great concern regarding food loss (FL) has been studied previously, but in an isolated way, disregarding interdependencies with other areas. This paper aims to go a step further by proposing a new procedure to assess different waste management alternatives based on the nexus approach by means of an integrated Water-Energy-Food-Climate Nexus Index

(WEFCNI). The environmental profile of the waste management techniques is determined using Life Cycle Assessment (LCA) which, in combination with Linear Programming (LP), explores the optimal aggregation of weighting factors that lead to an aggregated nexus index. The management of residues from the anchovy canning industry in Cantabria (Spain) has been used as a case study, considering the three current applied alternatives: (i) valorisation of FL as animal feed in aquaculture (food waste-to-food approach), (ii) incineration of FL with energy recovery, and (iii) landfilling with biogas recovery. The last two considered the use of energy recovered to produce a new aquaculture product (food waste-to-energy-to-food scenarios). The results indicate that incineration is the best performing scenario when the nutritional energy provided by the valorisation alternative is not high enough and the valorisation technology presents the highest water consumption. Therefore, a minimisation in the consumption of natural resources is suggested in order to improve the application of circular economy within the sector. The use of the nexus index as an environmental management tool is extendable to any food system with the aim of facilitating the decision-making process in the development of more sustainable products.

1. Introduction

Historically, solid waste management was shaped to serve a linear economy approach, in which the production cycle covers the following stages: raw material extraction, production, distribution and consumption, and disposal (Pietzsch et al. 2017). Consequently, more than 1.9 billion metric tons of solid waste are generated annually worldwide (Waste Atlas, 2018), of which over 1.3 billion metric tons correspond to products that are wasted or lost throughout the food supply chain - FSC (FAO, 2011a; Stoknes et al. 2016). This current level of food loss (FL) is equivalent to approximately one-third of the total global food production, and leads to significant environmental impacts, as well as to economic and social

costs (Manfredi and Cristobal, 2016). For example, annual food loss or waste leads to the emission of 3.3 Gt of CO₂ eq., the consumption of 250 km³ of surface and groundwater, the occupation of nearly 28% of the world's agricultural land and generates 1055 billion USD in economic costs (FAO, 2011b). Paradoxically, from a social point of view, roughly 800 million people on the planet are suffering from chronic undernourishment (FAO, 2014a).

Despite these worrying indicators, the problem of food waste (FW) and FL is currently on the rise, concerning all actors in the FSC (Giroto et al. 2015). However, there is a certain degree of ambiguity between FL and FW since both terms have been widely used by management entities (Kibler et al. 2018). This leads to a debate in the literature regarding the definition of FL and FW (Chaboud, 2017). One of the most widespread definitions is the one provided by FAO (2011), which described FL as the loss that occurs in the production, post-harvest, processing and distribution stages of the FSC, while FW is the loss that take places at the retail and consumer stages. However, such definition attributed a moral baggage to the final supply stages, while there could be losses taking place at primary production stages caused by the actions and behaviours at the retail stage. Therefore, the definition was updated to consider FL as the decrease in quantity and quality of food at any stage of the supply chain, while FW referred to the part of FL removed from the supply chain by choice (FAO, 2014c). The need of distinguishing between edible FW and non-edible FW has also been highlighted by some authors (Zorpas et al., 2018). Consequently, within the EU, FW is generally assumed to mean all of the food wasted from the food supply chain still perfectly edible and fit for human consumption. The environmental, economic and social problems caused by the generation of FL and FW urge to shift from the concept of linear economy to a production process focused on a circular economy perspective. This concept aims at keeping the added value in products, materials and resources for as long as possible and minimizing waste

generation. In this context, waste policy around the world is increasingly moving from the “prevention of waste” to a “sustainable materials policy” (Silva et al. 2017). In fact, the European Commission adopted the Communication entitled “Towards a circular economy: a zero waste programme for Europe” (EC, 2014), which includes actions to reduce by 35% landfilling of bio-waste by 2016, except those Member States who landfilled more than 80% of their municipal waste in 1995 which can apply for a prolongation of the time limits not exceeding four years (2020) (EC, 1999). Moreover, this communication shows how industrial symbiosis can move society towards zero-waste considering the reinsertion of waste into new production processes (Pérez-Camacho et al. 2017). In this sense, the reduction and/or management of FL and FW is based on the “solid waste hierarchy” (EC, 2008). According to this classification, FL and FW prevention activities are the preferred option as they have greater potential for improved environmental and socio-economic outcomes (Imbert, 2017), while landfilling seems to be the least preferable waste treatment. However, the implementation of circular economy in food waste management still seems to be at its initial stages, mainly focused on recycling and recovery instead of reusing, as shown in Figure 1 (Ghisellini et al. 2016). In this sense, the evaluation of the most environmentally-friendly FL management scenarios requires the use of environmental tools, such as Life Cycle Assessment (LCA), which have been increasingly used in recent years.

Figure 1. Graphical representation of the waste hierarchy for food and beverages adapted from the Waste Framework Directive 2008/98/EC (WRAP, 2017).

For instance, Papargyropoulou et al. (2014) proposed a framework to identify and prioritise the most appropriate options for prevention and management of FL applying the

waste hierarchy perspective together with the consideration of the three dimensions of sustainability (environmental, economic and social). In the United Kingdom, the National Research and Waste Forum Household Waste Prevention Toolkit, which is widely used, monitors and evaluates FW prevention by means of pilot cases (Read et al. 2009). The LCA methodology (ISO 2006a and 2006b) was used to compare the effect on greenhouse gas (GHG) emissions of different FW management scenarios at different levels of the waste hierarchy in Uppsala (Sweden) (Eriksson et al. 2015) and the effect on other environmental indicators, such as ozone depletion, smog, acidification and eutrophication, in the organic waste composting in the United States (Saer et al. 2013). Cristobal et al. (2016) combined LCA and Data Envelopment Analysis (DEA) to identify efficient and inefficient options of FW management and proposed a joint methodology using LCA and mathematical programming to address the situation in which a decision-maker has to design a FW prevention programme considering limited economic resources (Cristobal et al. 2017). Moreover, Manfredi and Cristóbal (2016) developed a six-step methodology based on life-cycle to evaluate environmental and economic sustainability of European FW management options. Other authors, such as Vandermeersch et al. (2014), analysed two FW valorisation scenarios (anaerobic digestion and animal feed) through exergy analysis, exergetic-LCA and traditional LCA. These authors pointed out that valorising FW for animal feed seems to be a better option only for some fractions of FW (i.e., those with low water content). Nevertheless, none of these studies use a “nexus” approach based on four indicators that combine nutritional -food- and environmental indicators -water, energy and climate- to address an adequate FL management approach. The term “nexus” implies that the action in one of the systems has impacts on the others (FAO, 2014b). Due to the interaction among the systems (Figure 2), any strategy that focuses on one system without considering its

connections with other systems may lead to acute consequences (El-Gafy, 2017). In this sense, the nexus approach is important to understand the synergies and trade-offs in order to develop response options to ensure the sustainability of the environment (FAO, 2014b). Anticipating potential trade-offs and synergies allows for design, appraise and prioritise response options that are viable across different sectors (FAO, 2014d). Previous research conducted to evaluate the nexus between resources has focused mainly on the relationship between two specific resources, usually energy and water (Graedel and van der Voet, 2010). For instance, studies by Lofman et al. (2002) and Siddiqi and Anadon (2011) discussed the energy - water nexus in California and the Middle East, respectively. However, due to the growing concerns linked to food security, efforts have been made to expand the nexus boundaries to one that focuses on analysing the relationship between energy, water and food resources (Al-Ansari et al. 2015). In fact, Kibler et al. (2018) proposed a conceptual model in which FW influences the Food-Energy-Water (FEW) nexus via two interconnected mechanisms, both driven by human behaviour and decision-making. Therefore, they stated that providing a full quantitative portrayal of FW within the FEW nexus based on a better understanding of variability among potential waste management options can support planning and decisions. In addition, the main nexus aspects considered (water, energy, food) can be modified to accommodate other aspects deemed relevant such as climate change.

In this context, the main objective of the current study is to expand the state-of-the-art of the nexus approach by developing a quantitative method to calculate an integrated Water-Energy-Food-Climate Nexus Index (WEFCNI) that facilitates the decision-making process in the management of FL. Decision-makers need improved tools in order to be better informed about trade-offs and synergies between different development and management choices, and to help them identify options on how to sustainably manage resources (FAO,

2014b). The nexus index can be used to develop strategies based on the circular economy concept to seek the optimal management pattern that minimises water and energy consumption, as well as GHG emissions, while maximizing their nutrient content. A case study focused on three waste-to-food strategies for the management of anchovy (*Engraulis encrasicolus*) canning industry wastes was selected to apply the nexus index proposed: (i) valorisation of FL as animal feed in aquaculture (food waste-to-food scenario), (ii) incineration of FL and (iii) landfilling with biogas recovery using the recovered energy to produce a new aquaculture product (food waste-to-energy-to-food scenarios). In this case study, bass (*Dicentrarchus labrax*) was the aquaculture product selected.

Figure 2. Graphical representation of the water-energy-food-climate nexus approach.

(Adapted from UNPAR (2017)).

2. Methodology

2.1. Decision-maker tools

Aggregated indexes are becoming popular and many computation methods are being proposed in the literature. Some approaches include statistical models such as principal component analysis (Mainali and Silveira, 2015) and multiple criteria decision analysis (MCDA) (De Luca et al., 2017). Regarding the latter, the analytic hierarchy process (AHP) is also being applied to sustainability assessments (Ziout et al., 2013), which relies on the judgement of experts to derive a priority scale (Saaty, 2008). Similarly, DEA is gaining importance recently (Galan-Martin et al. 2016), since it can derive objective weights using linear programming (LP) tools without

1 making any previous assumption on data, as opposed to principal component analysis
2 or AHP.

3 Since the 1990s, LP has been combined with Life Cycle Assessment (LCA) to aid
4 decision-making in sustainability studies (Steubin et al. 2016) or even to address the
5 problem backwards, estimating the value ranges where the weights attached to a set
6 of environmental impacts must lie (Cortés-Borda et al. 2013).

7 2.2. WEFC Nexus methodology

8 Currently, there is no universally recognised methodology for nexus analysis. However,
9 LCA is particularly important for understanding the interconnections in the nexus, as it
10 enables the consideration of entire supply chains which are increasingly globalised, with the
11 production and consumption often occurring in different parts of the world and affecting the
12 nexus in differing ways, depending on the region.

13 The proposed procedure, based on a previous study of García-Herrero et al. (2017a),
14 combines the LCA methodology and LP optimisation. LCA is applied considering the
15 recommendations provided by the ISO 14040 and 14044 standards (ISO 2006a, b) as shown
16 in Figure 3. In this study, the environmental results (the consumption of water and energy
17 and climate change) and the nutritional content are summarised into the four indicators
18 considered for the estimation of WEFCNI. The combination of both LCA and LP allows
19 estimating the weighting factors that lead to an optimised WEFCNI.

20 2.1.1. Goal and scope

21 The goal and scope definition produces a fairly accurate specification of the product or
22 products to be investigated and defines the intended application of the study in terms of the
23 system boundaries and a functional unit – FU (Rebitzer et al. 2004; Guinée et al. 1993). In
24 addition to this information, this step defines the allocation procedures, cut-off rules,

assumptions and the level of detail considered (Margallo et al. 2014b). At this stage, the core criterion in the comparison of the relevant product variations is the FU (Guineé et al. 1993). Moreover, the choices and assumptions made during system modelling, especially with respect to the system boundaries and what processes to include within these boundaries, are often decisive for the result of an LCA study.

2.1.2. *Life Cycle Inventory*

In the Life Cycle Inventory (LCI) stage, all relevant inputs and outputs for the process in a specific year are gathered (Margallo et al. 2014a). The source, quality and geographical and temporal representativeness of data are also considered in this step. Data collection is often the most work- and time-consuming step in LCA studies (Retbitzer et al. 2014). The result of the LCI stage is an inventory of environmental exchanges based on the allocation rules and assumption defined in the previous step related to the FU (Guineé et al. 1993).

2.1.3. *Life Cycle Impact Assessment*

The Life Cycle Impact Assessment (LCIA) step quantifies the potential for resources consumption and environmental impact over all of the stages involved in the supply chain. LCIA comprises two stages according to the ISO standards (Margallo et al. 2014b):

- Classification: it includes the selection of the impact categories and characterisation models.
- Characterisation: the impact of each emission or resource consumption is modelled quantitatively using a characterisation factor. This factor expresses how much that flow contributes to the specific impact category under assessment.

- Normalisation (optional): it relates the magnitude of impacts in different impact categories to references values.
- Weighting (optional): the different environmental impact categories are ranked according to their relative importance. Weighting may be necessary when trade-off situations occur in LCAs which are being used for comparing alternative process/products.

2.1.4. Definition of the four indicators referred to the functional unit (classification and characterisation)

The proposed methodology includes all the LCIA stages, starting with classification. Firstly, four indicators referred to the FU were defined: water consumption (W_c), energy consumption (E_c), Food (P_c) and Climate (C_{ei}). Nevertheless, not all of the indicators require a characterisation step. For instance, in the case of the P_c indicator, it allows measuring the nutritional footprint of the system under study without characterisation. This indicator does not require a change from nutritional values to a common unit, i.e. kg CO₂ eq. Thus, after the classification, a normalisation procedure is conducted. The nexus indicators are explained below:

Water consumption (W_c)

This indicator represents the water consumption. Water consumption can be divided into direct and indirect water use. Food waste management alternatives use water directly as a resource and indirectly as in the water consumed in producing the inputs needed in the different scenarios. W_c is calculated applying Equation 1.

$$W_c(s) = w_d + w_i \quad (1)$$

Where w_d is the direct water consumption (m^3/FU) (for example, in the incineration process), w_i is the indirect water consumption (m^3/FU) (e.g., the water used for the production of chemical products required in the incineration and landfill processes or the water consumed for the manufacture of ingredients used in the fishmeal production) and s represents each scenario analysed.

Energy consumption (E_c)

This indicator represents energy consumption. Similarly to W_c , energy consumption for food waste management alternatives can be categorised into direct and indirect energy use. Food waste management uses energy directly, as fuel or electricity to operate machinery and equipment, and indirectly, as in the energy consumed in producing the inputs used in the different scenarios under study. E_c is calculated following Equation 2.

$$E_c(s) = e_d + e_i \quad (2)$$

Where e_d is the direct energy consumption (e.g. electricity or diesel oil for machinery operation) (MJ/FU) and e_i represents the indirect energy consumption (MJ/FU). e_d and e_i can be calculated following Equations 3 and 4.

$$e_d(s) = \sum_{k=1}^k q_k h_k \quad (3)$$

$$e_i(s) = \sum_{n=1}^n q_n h_n \quad (4)$$

Where k represents electricity and diesel oil, n represents the rest of inputs used in the different scenarios under study, q is the energy equivalent measured in MJ per unit of input flow (i.e. MJ/h for machinery operation) and h is the activity whose unit depends on the input flow (i.e. h/FU for machinery operation) (El-Gafy, 2017).

Food (P_c)

This indicator represents the protein content of the food product obtained from the management of FW. P_c is calculated applying Equation 5.

$$P_c(s) = m_f \cdot p_f \quad (5)$$

Where m_f represents the mass of food product obtained from the food waste management (kg food product/FU) and p_f is the protein content per 100 g of food product (kg protein/kg of food product). Although protein is only one of the numerous nutrients available for food characterisation, it is one of the most representative for seafood products, since fish and other seafood species (e.g., cephalopods or molluscs) are a good dietary source of animal protein while reducing the content of saturated fats, as opposed to red meat (USDA, 2014). The edible protein energy content has already been used to perform a critical comparison of seafood products landed in Galicia and Cantabria applying the edible protein energy return on investment (ep-EROI) indicator (Vázquez-Rowe et al. 2014; Laso et al. 2018).

Climate (C_{ei})

This indicator is represented by the environmental indicator Global Warming Potential (GWP) (kg CO₂ eq.) associated with the food waste management alternatives selected. The assessment method employed to compute the results is IPCC 2013, applying a 100 year time horizon perspective (IPCC, 2013). GWP is calculated following Equation 6.

$$C_{ei}(s) = \sum_{i=1}^i m_i \cdot EF_i \quad (6)$$

Where i represents the substances that contribute to the GWP, m is the weight of substance i emitted (kg/FU) and EF is the emission factor of substance i (kg CO₂ eq./kg i).

2.1.5. Water-energy-food-climate nexus index (normalisation and weighting)

Based on the described methodology, firstly, normalisation is required to render the variables comparable. Normalisation facilitates the comparison among indicators, while the weighting procedure ranks the different environmental categories according to their relative importance (García-Herrero et al. 2017a). Hence, internal normalisation was applied to each nexus indicator according to Equation 7.

$$X_i^* = \frac{X_i}{X_i^{ref}} \quad (7)$$

$$X_j^* = \frac{X_j}{X_j^{ref}} \quad (8)$$

Where X_i represents the value of the different i nexus indicators ($X_1 = W_c$; $X_2 = E_c$; $X_4 = C_{ei}$) and X_j represents the value of the j nexus indicator ($X_3 = P_c$); X_i^* and X_j^* are the normalised values of X_i and X_j ; and X_i^{ref} and X_j^{ref} are the reference values for each nexus indicator, that in this case, is represented by the maximum value of the sample.

The nexus index was calculated by weighting applying Equation 8:

$$WEFCNI = \sum_{i=1}^i \alpha_i \cdot X_i^* - \sum_{j=1}^j \alpha_j \cdot X_j^* \quad (9)$$

Where α_i and α_j are the weighting factors that serve at the aggregation of the four indicators into a single composite index, X_i^* represents the normalised indicators to minimise (in this case W_c , E_c and C_{ei}), while X_j^* represents the indicators to maximise (i.e., P_c).

Equal weighting is usually applied in the literature as a first approximation for constructing a composite index (Zhou et al. 2012). Therefore, for comparison purposes, the four indicators are first assumed to be equally relevant. However, this approach can disguise the absence of statistical or empirical bases for determining the weights. Therefore, the current study applies a LP weighting approach based on a previous study

by Garcia-Herrero et al. (2017a) to calculate the optimum values of α_i and α_j and estimate the WEFCNI for each scenario. Given the uncertainty nature of the decision-making area explored, the values of the weighting factors have been determined according to three different criteria based on decision theory: optimistic criteria, i.e. maximising the objective function that lead to the comparison of scenarios in best terms case; pessimistic criteria, i.e. minimising the objective function to enable the comparison of scenarios under worst possible conditions and equiprobability criteria, i.e. using average weighing factors from the two previous procedures. The lower and upper optimum values of α_i and α_j for each scenario were determined by following the methodological procedure outlined in Figure 3. Equation 9 becomes the objective function of the model and, thus, it is optimised to estimate the lower and upper weighting factors that lead to the nexus index, satisfying Equation 10.

$$s. t. \quad \sum_{i=1}^i \alpha_i + \sum_{j=1}^j \alpha_j = 1 \quad (10)$$

The values of the weighting factors were determined by correlating the different metrics. In a previous study, a linear relationship was observed between the consumption of energy and the rest of indicators when the influence of an energy-intensive process was studied (García-Herrero et al. 2017a). In this study, electricity and bass production processes have been assessed to determine the correlation between primary energy consumption and the remaining metrics. An accurate linear approximation ($R^2 > 0.999$) has been found between X_2^* and each indicator, and these relationships have been taken as constraints for determining the weighting factors α_i and α_j (Equations 10-11). Further information about the relationship between indicators is collected in the Supporting Material (SM).

$$\text{s.t. } \alpha_i X_i^* \leq w_{1,i} \alpha_2 X_2^* \quad (11)$$

$$\alpha_j X_j^* \leq w_{2,i} \alpha_2 X_2^* \quad (12)$$

where $w_{1,i}$ and $w_{2,j}$ are the slope factors to determine α_i and α_j , respectively. It has also been assumed that every indicator has a minimum weight ($\alpha_{i,min} = \alpha_{j,min} = 0.001$) so that none of them are neglected (García-Herrero et al. 2017a).

Figure 3. Graphical representation of the water-energy-food-climate assessment method proposed.

3. Energy analysis: food loss energy return on investment (FL-EROI)

The Energy Return on Investment (EROI) method is used to examine the energy return from an energy-generating process relative to the energy used to derive end products (Gupta and Hall, 2011). The most common use of EROI is within the energy sector (Hall and Cleveland, 1981), but broad comparisons of protein sources can be performed by calculating a dimensionless ratio of the edible protein energy content of an animal related to the total industrial energy expended in its production/acquisition. This approach to EROI computation has been referred to in the literature as the edible protein energy return on investment (ep-EROI) (Vázquez-Rowe et al. 2014).

The current study applies the ep-EROI method to assess different FL management options. However, considering that the focus is on FL, the term ep-EROI has been modified to FL-EROI, in order to account for the ratio of the output of food measured in food energy (bass protein value) to energy use for the anchovy residues management system (Equation 12).

$$FL - EROI = \frac{\text{Output energy (energy provided to consumer)[MJ]}}{\text{Input energy (primary energy invested)[MJ]}} \quad (13)$$

4. Case study: management of the FL generated in the anchovy canning industry

Spain is the top European producer of canned seafood with more than 343,000 t/year of product, valued at 1,500 million euros (FAO, 2015). Among the different types of fish species, anchovy is the fifth most popular in Spain in terms of per capita consumption (Eurofish, 2012), being the quality of canned anchovies from Northern Spain, namely Cantabria, recognised worldwide. Consumers consider canned anchovies as a “gourmet” food product due to its handmade and traditional processing. However, throughout the canning process, large amounts of anchovy residues are generated, which must be managed in a sustainable way. This is consistent with other fish and seafood products. In fact, in Europe, approximately 30% of FL and FW is related to capture, post-catch, processing, distribution and consumption of fish and seafood. More specifically, the processing stage alone accounts for 5% of the FL (FAO, 2011a).

In the canning factory, fish are beheaded and placed in layers with a bed of salt between each layer for 6 months. After curing, the skin is removed by means of cold and hot water (scalding), and each anchovy is cut and filleted by hand. Anchovy fillets are then packed in cans filled with olive oil. Finally, the cans are sealed, washed, codified and packed. Throughout this process, approximately 60% of the anchovy wet weight is lost.

Previous studies assessed the environmental performance of several management alternatives of anchovy FL: valorisation, incineration and landfilling (Laso et al. 2016). Landfilling was the least environmentally-friendly alternative, presenting a higher GWP than the incineration and valorisation alternatives. Valorisation of anchovy FL was the most favourable management option. As a novelty, in addition to the evaluation of the management

alternatives under an environmental point of view, this study includes the energetic and nutritional variables combining them with water consumption and expands the system boundaries to include the consumption of the new food product obtained and, thereby, closing the loop. Therefore, the system function is the management of a residue to obtain protein by means of the consumption of a new food product. To this end, the FU defined was described as the “management of 1 metric ton of anchovy residues from the canning industry to obtain protein”.

The methodology described in this paper is focused on two approaches: “food waste-to-energy-to-food” and “food waste-to-food”, as presented in Figure 4. The concept of “food waste-to-food” following refers to the use of this waste as a raw material for feed formulation. In this sense, valorisation of food waste reduces the environmental effect associated with animal feed production, maximising resource efficiency and contributing to competitiveness of feed producers (San Martín et al., 2016). In this study, the “food waste-to-food” perspective involves the “food waste-to-energy-to-food” approach, which is an indirect way of valorisation, recovering energy from the landfilling and incineration and using it in produce animal feed. Based on these perspectives, the case study considers three scenarios: landfilling with biogas recovery, incineration and valorisation, as explained below.

- Food waste-to-energy-to-food. This approach includes landfilling with biogas recovery and incineration. In both scenarios, the management of anchovy FL generates energy, which can be employed in the production of fishmeal to feed bass in an aquaculture system. The electricity recovered from both processes is transformed into its equivalent amount of primary energy and employed in the production of fishmeal in a reduction plant and in a bass aquaculture plant. The reduction plant with a yield of 21% processes 9600 t/year of fish residues to produce

1 fishmeal (Fréon et al. 2017). The aquaculture system consists of an inland farm
2 specialised in intensive rearing of sea bass with a global production capacity of 2,500
3 metric tons per year. The growing stage is performed in a flow-through system, also
4 referred to as a traditional raceway (TR), with a total capacity of 89,280 m³. Tanks
5 are placed in parallel and separated by passageways. The entry flow is approximately
6 45 l/s. The sector is supplied with sea water by a pumping station consisting of six
7 pumps (four of them with a capacity of 2 m³/s and two of 0.6 m³/s). Three of them
8 operate all year round, whereas the others are activated only during the summer
9 season (from May to September). Wastewater is directly evacuated to the sea by
10 gravity (Jerbi et al. 2012). These scenarios represents a particular system expansion
11 conducted to make the three scenarios comparable and to estimate the food indicator
12 for the scenarios not providing feed as direct output. System expansion is usually
13 applied to include the additional functions related to co-products, wherever it is
14 possible (Garcia-Herrero et al. 2017b).

15 *Landfilling.* Anchovy FL was transported by road from the canning plant to a landfill
16 located at 17 km. The landfill comprises gas and leachate treatment. The latter
17 includes active carbon and flocculation/precipitation processing including sludge
18 treatment and deposition. Moreover, sealing materials (clay, mineral coating, PE
19 film) and diesel for the compactor are also included in the LCI. This dataset is valid
20 for landfill of municipal solid waste in Spain, Portugal and Greece.

21 *Incineration.* The waste-to-energy (WtE) plant is composed of one incineration line
22 with a capacity of 12.0 t/h, treating waste with a low heating value (LHV) of about
23 2,800 kcal/kg. The combustion is conducted in a roller grate system that reaches a
24 temperature of 1025°C. Flue gases are treated by means of a selective non-catalytic

reduction system (for NO_x), bag filter (dust, dioxins, etc.) and semidry scrubbers (acid gases). The main solid residues are fly and bottom ashes. The latter are subject to magnetic separation to recover the ferrous materials; the inert materials are sent to the landfill close to the WtE plant. Fly ashes, classified as hazardous material, are stabilised and sent to an inert landfill (Margallo et al. 2014). Finally, anchovy FL was transported by road from the canning plant to a waste-to-energy plant located at 17 km.

- Food waste-to-food. This approach includes one single scenario: the valorisation of the FL into fishmeal. It was considered that anchovy FL was sent to a reduction plant located next to the canning plant and that fishmeal production is 100% sourced from anchovy FL. The fishmeal was transported by road to an aquaculture plant situated 100 km from the reduction plant and it was used to feed the bass raised in the aquaculture plant. The transportation of fishmeal to the aquaculture plant was carried out considering a Euro 4 truck with a maximum total capacity of 28 t, which circulated on a motorway.

These three scenarios (landfill, incineration and valorisation) were selected because they are the three main waste management alternatives carried out in Cantabria.

Figure 4. Graphical representation of the system boundaries and of the anchovy food loss scenarios under study.

Regarding allocation rules, in the incineration treatment, part of the energy generated is recirculated to the WtE plant, providing the system with an additional function. This situation was handled through system expansion by subtracting the function of the alternative system

(production of electricity) from the system under study. The Spanish electricity mix in 2016, included in the PE GaBi database (PE International, 2014) was selected as the function replaced in the system expansion.

On the other hand, due to the fact that the landfill and incineration scenarios are used to manage wastes that include more fractions along with the FW considered in this paper, allocation was done in order to estimate the water and energy consumption and CO₂ emissions of the organic matter. For the landfill scenario, water and energy consumption were allocated by mass considering that the organic matter represents 44%. This percentage varies according to the region or country (Suthar and Singh, 2015). For GWP, the decomposition factor of the organic matter was used. Regarding incineration, for water consumption we used a mass allocation; for energy consumption, the allocation was based on the high heating value; and for GWP we used the carbon content. Figure S4 and Tables S1-S4 with the composition of the residue and allocations are shown in the SM.

Regarding data acquisition, the LCI was based on primary data provided by an industrial anchovy canning plant in Cantabria, and complemented with bibliographical data. Table 1 shows a list of the data sources. More information about the LCI is collected in the SM.

Table 1. Data sources for life cycle inventory of the water-energy-food-climate assessment method proposed.

5. Results

Before carrying out the nexus analysis, the scenarios under study were evaluated under an energy perspective by means of the FL-EROI indicator defined in section 3. Table 2 summarises the main results of the energy analysis.

Table 2. Results obtained from the energy balance of the management of 1 metric ton of anchovy FL in the scenarios under study.

The landfilling and incineration of 1 t of anchovy FL (food waste-to-energy-to-food approach) required 598 MJ and 159 MJ of primary energy, respectively. These processes recovered 132 MJ of energy through biogas recovery in the landfill and 937 MJ of energy through the incineration. Regarding the latter, approximately 14.3% of the energy obtained in the incineration process (134 MJ) was recirculated to the WtE plant to meet plant energy requirements, and the remaining (803 MJ) was employed in the production of fishmeal to be used in a bass aquaculture system, as well as the 132 MJ recovered in the landfill. The Spanish electricity mix in 2016 was used to transform the electricity recovered in both processes into primary energy. This amount of primary energy allowed the production of 13 kg of bass in the landfill scenario and 78 kg of bass in the incineration scenario. In contrast, the valorisation of anchovy residues (food waste-to-food approach) generated 138 kg of bass. The yield of the valorisation was influenced by the yield of the reduction plant (i.e., 21%).

The amount of bass produced can be translated into energy to nourish consumers by means of the bass edible content (60%) and its protein content (22%). In addition, it was assumed that the default value of energy protein content was 16.73 MJ per kg of protein (Vázquez-Rowe et al. 2014). Landfilling and incineration produced 28 MJ and 188 MJ, respectively, whereas valorisation generated 333 MJ. Therefore, the landfilling scenario added up to 2 kg of fish protein, incineration 11 kg and valorisation 20 kg. These results indicate that, under a food security point of view and considering a consumer approach, the

valorisation scenario seems to be the most preferable option, providing substantially more energy to the consumers.

The total primary energy invested in landfilling was 949 MJ, the lowest value throughout the scenarios evaluated. This amount was the sum of the energy required in the landfilling (598 MJ) and the energy invested in the production of bass (351 MJ). The incineration scenario, in contrast, showed a substantially higher thirst for energy: 2294 MJ. Similarly, this amount was the sum of the energy required in incineration process (159 MJ) and the energy invested in the production of bass (2135 MJ). Regarding the valorisation process, it invested the highest amount of energy: 2956 MJ to manage 1 t of anchovy FL. With these results, the FL-EROI was calculated following Equation 12. Valorisation presents the highest FL-EROI (11%), somewhat higher than incineration (8%). Finally, landfilling presented a low rate of 3%.

In addition, calculated W_c and E_c , P_c and GWP indicators per FU are collected in Table 3. Within each variable, the environmental scores have been ranked using colour coding. Higher negative impacts and lower nutritional content are highlighted in red, while lower negative impacts and higher nutritional content are coloured in green. Accordingly, the valorisation scenario presented the highest consumption of energy $2.96 \cdot 10^3$ MJ per FU. Interestingly, it also achieved the highest amount of bass produced and, consequently, the highest amount of protein content available for direct human consumption (20 kg protein). In terms of water and energy consumption, as shown in Figure 5, in the valorisation scenario there was only indirect use of water due to the different processes involved in the supply chain, as explained in the previous section. For instance, the production of diesel represents 66% of total water consumption and 93% of total energy consumption. Moreover, the production of electricity consumes 29% and 5% of total water and energy, respectively. Other

processes, such as the production of polypropylene for the fishmeal bags and the transport, represent less than 5% of total impacts.

Figure 5 also shows the contribution of different processes to total water and energy consumption in the incineration scenario. The direct use of water represents 42% of water-related impacts, but only 2% of total energy requirements. In addition, 16% of water-related impacts are attributable to the production of chemical reagents (lime, urea and calcium hydroxide). In terms of energy their relative contribution is somewhat higher (26%). The use of diesel to fuel supply chain activities constitutes one of the main contributors: 41% for water impacts and 56% for energy. Other processes, such as the transportation, contribute less than 5% in both indicators.

In terms of GHG emissions, landfilling presents the highest environmental impact, 936 kg CO₂ eq. per FU, whereas valorisation produced 61 kg CO₂ eq. and incineration 12 kg CO₂ eq. Emissions occurring in the landfill itself due to organic waste decay account for most of the impact in the landfilling scenario, whereas biogas recovery did not show much influence on the environmental performance. As observed, the decision-making process is not straightforward, as there is no scenario that presents the best (or worst) scores for every metric. This is the reason why the development of a nexus index is essential to identify the best management alternative.

Table 3. Water consumption (W_c), energy consumption (E_c), protein content (P_c) and environmental impact (C_{ei}) for each scenario analysed.

Figure 5. Relative contribution to water and energy consumption of the different processes involved in the valorisation and incineration scenarios.

Once the environmental analysis of the systems is assessed, the methodology described is applied to simplify the decision-making process. Given a set of environmental impacts for each alternative scenario, the optimisation process determines the weighting factors that conduct to a minimum value of the WEFCNI. Thereafter, the LCA outputs are normalised (X_i^*) and posed into mathematical terms based on the linear model described in Equations 8-11. Thenceforth, the weighting factors that lead to the three different WEFCNI cases are determined. The GAMS software (2017) was used to carry out the optimisation. This procedure does not modify the previously calculated individual impacts (X_i), but influences the relevance attributed to each of them. Table 4 shows the resulting ranges for the weighting factors attached to each indicator and each scenario, as well as the average weighting factors. X_2 is the indicator to which the highest average importance is attributed ($\alpha_2 = 0.18-0.84$), since its influence is reflected in the remaining categories, avoiding double counting. The second major importance is assigned to X_4 ($\alpha_3 = 0.007-0.49$), especially for incineration and valorisation scenarios under best case terms since these are the scenarios with the lowest climate score. Results in Table 4 suggest that, for the specific case of the management of anchovy residues, energy (X_2) and climate (X_3) appear to be the decisive nexus variables.

Once the optimisation was performed, weighting was conducted to obtain the WEFCNI. Results for each scenario are depicted in Figure 6, where the y-axis represents the dimensionless global nexus index under optimistic, pessimistic and equiprobability criteria. It can be appreciated that both optimistic and pessimistic criteria result in the same ranking for the scenarios under study, but differ in the values obtained. In this sense, the valorisation scenario appears to be the worst alternative for the management of fish waste under both

pessimistic and optimistic criteria. This is essentially due to the fact that this scenario is the most energy intensive, consuming on average 3 times more energy than the other scenarios. Moreover, it just delivers 1.7 times the quantity of proteins estimated for the incineration scenario, requires 7.2 times more water and emits 3.1 times more CO₂ eq. (see Table 3). These results can be somewhat controversial, since the management option with a higher utilisation of anchovy (valorisation) does not present the best performance under a WEFC nexus point of view. This is in agreement with Cobo et al. (2018), which state that enhancing circularity of resources does not necessarily entail that the overall consumption of natural resources and the environment burdens generated of the system decrease. Similarly, Kleemann et al. (2017) stated that a closed loop system is only possible for a few materials and the circular economy needs quite detailed research when it comes to deriving specific resource management alternatives. Similarly, it is also the most water intensive scenario. On the other hand, the landfill scenario was identified as the best performing scenario under these conditions, given the fact that this is the least energy intensive scenario. However, it emits 25 times more CO₂ eq than the remaining scenarios and produces 9 times less protein. Consequently, it is penalised when the equiprobability approach is followed, becoming the worst possible alternative. Equiprobability results seem to deliver the less aggressive results, which agree with the qualitative comparison among scenarios, while comparing them under same conditions.

Table 4. Optimised results for the management of anchovy residues in Cantabria after applying the LP model.

Figure 6. Water-Energy-Food-Climate Nexus Index (WEFCNI) results for each management scenario assessed.

6. Conclusions

The current study provides a method for decision-makers to holistically assess the interdependencies affecting food security based on the assessment of water, energy, food and climate. A Water-Energy-Food-Climate Nexus Index (WEFCNI) indicator is proposed based on the direct and indirect consumption of water and energy for food production, nutritional food content and GHG emissions related to waste management. The procedure was applied to three FL management alternatives to evaluate the best option to manage anchovy residues from the canning industry in Cantabria: landfill, incineration and valorisation.

In a previous energy analysis using the FL-EROI indicator, the valorisation scenario seemed to be the best option to manage anchovy FL (11%), followed by the incineration alternative (8%). Given the inherent uncertainty of the decision-making area explored, the values of the weighting factors have been determined according to three different criteria based on decision theory: optimistic, pessimistic and equiprobability criteria. Interestingly, once the WEFCNI was calculated under an equiprobability approach, the optimised results indicated that the incineration alternative (waste-to-energy-to-food approach) was the best scenario because it presents the lowest WEFCNI value (0.310), while landfilling was the worst scenario (WEFCNI= 0.0.475). In general, the WEFCNI suggests that incineration is the best option for anchovy FL management when the EROI provided by the valorisation alternative is not high enough and the valorisation technology presents the largest energy consumption. Moreover, these results highlighted the fact that each waste management alternative has a critical nexus variable associated, highlighting the need of assessing the interdependencies among the different WEFCNI areas to make integrated decisions. However, these results should be analysed with care since they are specific for the

management of FL from the Cantabrian anchovy canning sector. Consequently, similar studies should be done, with site-specific data, in order to evaluate the best waste management option in other food systems. Finally, results highlight the need to improve the application of circular economy in the food sector, using waste as a raw material in the production of new food products and minimising the consumption of resources. Currently, circular economy is still a disperse concept that requires a deeper analysis from an environmental sustainability perspective. In this sense, in the agri-food sector it is necessary to identify the main challenges regarding circular economy to contribute to global sustainability, in particular, to contribute to food waste management alternatives. For this, it is essential to approach circular economy with an open mind, willing to overcome obstacles related to the traditional concepts in waste management. According to the results of this study, the definition of specific strategies for each food group should be addressed, taking into account the rebound effect that a decision could have in other environmental compartments of the nexus. The final objective should be attracting both the business and policy-making communities to sustainable development. Therefore, further scientific research is required in order to secure that the actual environmental impact of circular economy works towards sustainability.

In this context, the method presented in the current study allows more integrative planning, development, policy-making, monitoring and evaluation by combining LCA with linear programming optimisation. In fact, its robustness permits its replication to numerous production systems in the agro-industrial sector, facilitating the decision making process by means of a single aggregated index.

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